Weighting Di-Boson Monte Carlo Events in Hadron Colliders

Gideon Bella[1]

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Abstract

A detailed study of the di-boson Monte Carlo programs PYTHIA, MC@NLO and the program of Baur, Han and Ohnemus (BHO) is performed. None of these programs cover all aspects of di-boson production. The BHO code is used to produce event weights emulating anomalous triple gauge couplings in PYTHIA and MC@NLO events. In the same way, boson spin information which is missing for most di-boson channels in MC@NLO can be introduced as well. This weighting code can be used to study systematic effects related to various aspects of the Monte Carlo generators, e.g. parton distribution functions. A detailed study comparing distributions of event samples generated with these three generators shows a nice agreement for events without jets. Some differences between the three samples are observed for events with jets. Most of these differences can be attributed to the different ways of jet production in the three programs.

Keywords: Hadron-Hadron Scattering, Standard Model, Spin and Polarization Effects

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[1]e-mail: bella@atlas2.tau.ac.il

1 Introduction

Di-boson production is one of the most interesting processes to test the Standard Model. At LEP2 e^+e^- collider [1], W^+W^- production has been used to investigate the properties of the W-boson, in particular its mass and decay branching fractions, and to measure the W-polarization. In addition, cross sections for W^+W^-, ZZ and $Z\gamma$ production have been measured and these processes have been used to look for anomalous Triple Gauge Couplings (TGC's).

As far as hadron colliders are concerned, the measurement of the W-boson properties is based on single W events where the production rate is by far higher than for di-bosons. Di-boson events are useful for cross-section measurements, TGC and polarization studies. Both Tevatron experiments, CDF [2] and DØ [3] have used their Run II data of $p\bar{p}$ collisions at center-of-mass energy of 1.96 GeV to measure cross sections for W^+W^-, $W^\pm Z$, ZZ, $W^\pm\gamma$ and $Z\gamma$ production and to set limits on the anomalous TGC's. The LHC sensitivity for all the anomalous TGC's is expected to improve with respect to the Tevatron, and for most anomalous couplings, also with respect to LEP2, due to the higher energies and larger event samples at the LHC. The TGC analysis is based on comparing measured and expected distributions of kinematic observables, and therefore, should rely on the best possible modelling of the di-boson Monte Carlo production. Moreover, di-boson events constitute an important background source for new particle searches, most notably the Higgs boson which, if massive enough, decays mainly into W^+W^- and ZZ final states. Consequently, the new particle discovery reach is affected by the quality of the Monte Carlo generators of the di-boson background channels.

Figure 1 shows many of the Feynman diagrams contributing to di-boson production at hadron colliders w/o outgoing partons. Diagrams (a) and (b) correspond to the 0th (leading) order (LO) in QCD, namely the Born cross-section without outgoing parton. Diagrams (c) and (d) are similar to (a) and (b), with the additional emission of one gluon, thus being 1st (next-to-leading) order (NLO). Since gluons are very abundant in the interacting protons, particularly at the high LHC energy, diagrams such as (e)-(h) should be included as well. One loop diagrams like (i) and (j) are 2nd order in QCD, but they interfere with the LO diagrams (a) and (b). This interference is then 1st order in QCD and should be included in any NLO calculation.

Consequently, in LO di-boson Monte Carlo generators, the result of the hard interaction between the incoming partons is the di-boson system, whereas NLO generators produce two types of events. The first type includes the di-boson system only, and is due to the LO diagrams (a) and (b), and their interference with the loop diagrams (i) and (j). One also adds the contribution of diagrams like (c) and (d), where the outgoing parton is either soft or collinear. This is needed because there are infra-red divergences both for real and virtual partons which cancel each other when added together. The soft parton is not observed at the final state. Since the interference term can be negative, the cross section for many of these events is negative and they are associated with negative weights.[2] The second type of events produced by the NLO generators is due to diagrams (c)-(h) with hard parton which is observed in the final state along with the two bosons. All these events have positive cross section and are generated with

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[2] In most cases, events are generated with some approximate distribution, and obtain a weight being equal to the ratio between the exact cross section value and the approximated expression used for generation. An unweighted event sample can be obtained, only for the case where all weights are positive, using a random number generator to reject part of the generated events.
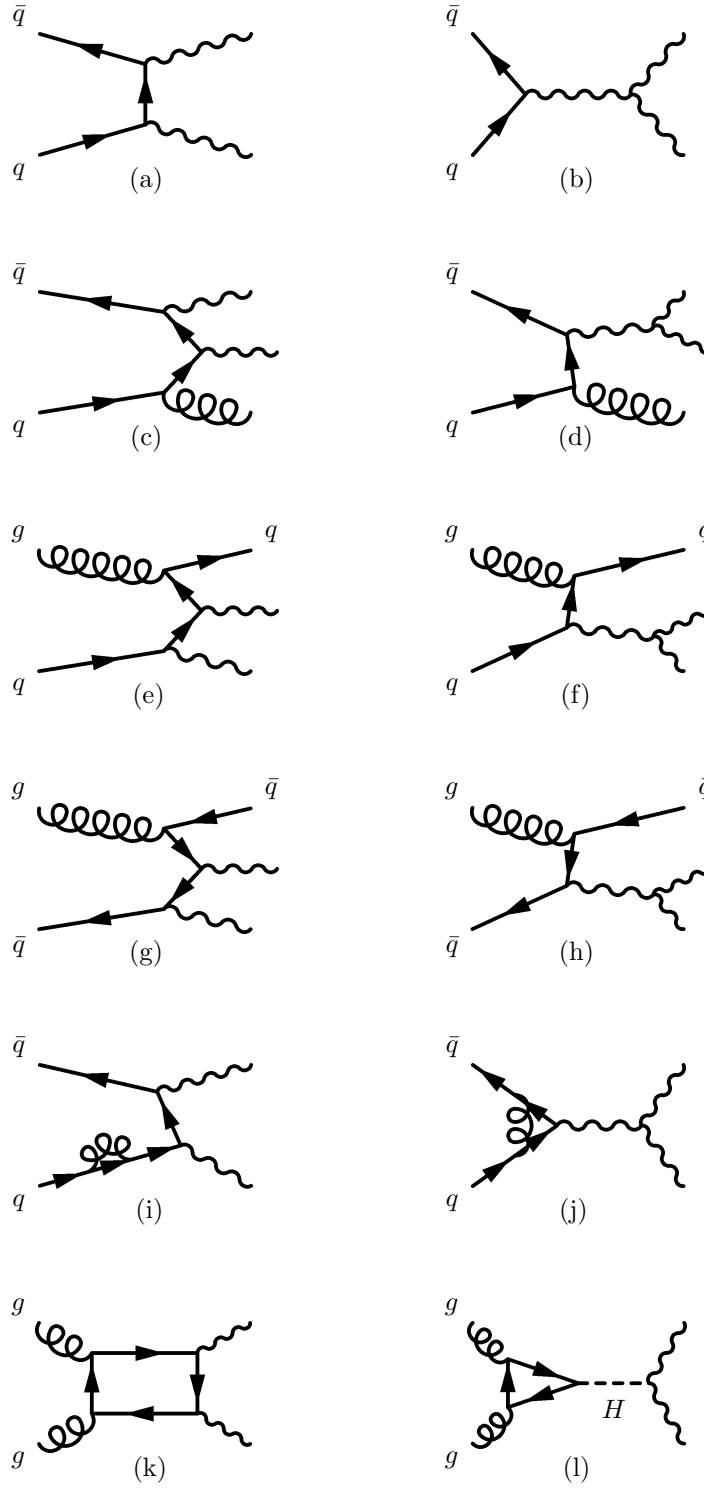
Figure 1: *Feynman diagrams contributing to di-boson production at hadron colliders*

positive weights.

The gluon-gluon fusion diagrams (k) and (l), which can produce only di-boson final states with zero charge (e.g. W^+W^-, ZZ), describe a separate process and do not interfere with the LO diagrams, thus contributing only to the next-to-next leading order (NNLO) in QCD. This is why those diagrams are missing from the NLO calculations but nevertheless, their contribution is not negligible [4], again due to the high abundance of gluons in the high energy interacting protons. Recently, the Monte Carlo programs gg2WW and gg2ZZ to generate W^+W^- and ZZ final states have become available [5]. These processes will not be further discussed in this note.

Several di-boson Monte Carlo generators exist. Each one of them includes some important aspects of the di-boson production, but, as will be described in the next section, none of them cover all the important aspects. In this report, we suggest to combine the advantages of two Monte Carlo programs, using one of the programs to generate the events and the second program to calculate a correction weight for each event in order to complement the physics aspects missing in the first program. This event weighting method will be described in the third section, and demonstrated with simulated data. The resulting distributions of kinematic observables of the different Monte Carlo generators will be compared and the differences will be discussed. The technical details of using our weighing program will be described in the Appendix.

2   Monte Carlo Generators

We examine three Monte Carlo generator programs, PYTHIA6.4, BHO and MC@NLO3.2.

The PYTHIA program [6] generates all possible di-boson pairs, W^+W^-, $W^\pm Z$, $W^\pm\gamma$, ZZ, $Z\gamma$ and $\gamma\gamma$. However, NLO effects are not included, and there is no implementation of anomalous couplings.

The program by Baur, Han and Ohnemus (BHO) [7] generates W^+W^-, $W^\pm Z$, $W^\pm\gamma$ and $Z\gamma$ events. Charged current WWγ ($\Delta\kappa_\gamma$, λ_γ) and WWZ ($\Delta\kappa_z$, λ_z, Δg_1^z) anomalous couplings [8] are implemented for W^+W^-, $W^\pm Z$ and $W^\pm\gamma$ production. For $Z\gamma$ production, there is an implementation of neutral current anomalous couplings which are missing in the standard model, $Z\gamma\gamma^*$ and $Z\gamma Z^*$(h_i^γ, h_i^Z, i=1,2,3,4)[3] [8]. The outgoing gauge bosons are produced with their nominal mass values without width. The events are weighted and the weight distribution for W^+W^- events at the LHC is shown in Fig. 2. This distribution is very broad, with a large number of negative weights. All these negative weights are associated with events of pure di-boson final state without any outgoing partons. Therefore, it is not possible to produce a sample of unweighted events. Moreover, having most of the events produced with very small weights is a serious problem for the LHC where a significant amount of CPU time is needed for the detector simulation of each event. Only the hard interaction between the incoming partons is simulated using the Matrix Element (ME) of the process, generating the decay products of the gauge bosons and possibly one outgoing parton, henceforth referred as ME parton or

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[3]These are couplings of the intermediate state off-shell photon or Z, denoted here by γ^*,Z^*, to the outgoing on-shell photon and Z.

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ME jet. However, the underlying event is ignored, and there is neither parton showering, nor hadronization, which is a serious disadvantage. Including the simulation of these missing parts, could be done by PYTHIA or HERWIG [9], using e.g. the Les Houches Accord [10]. However, it would introduce double counting of the ME parton, and the other partons produced in the parton shower simulation, henceforth referred as SH partons or SH jets. Consequently, BHO generated events cannot be used as input for full detector simulation.
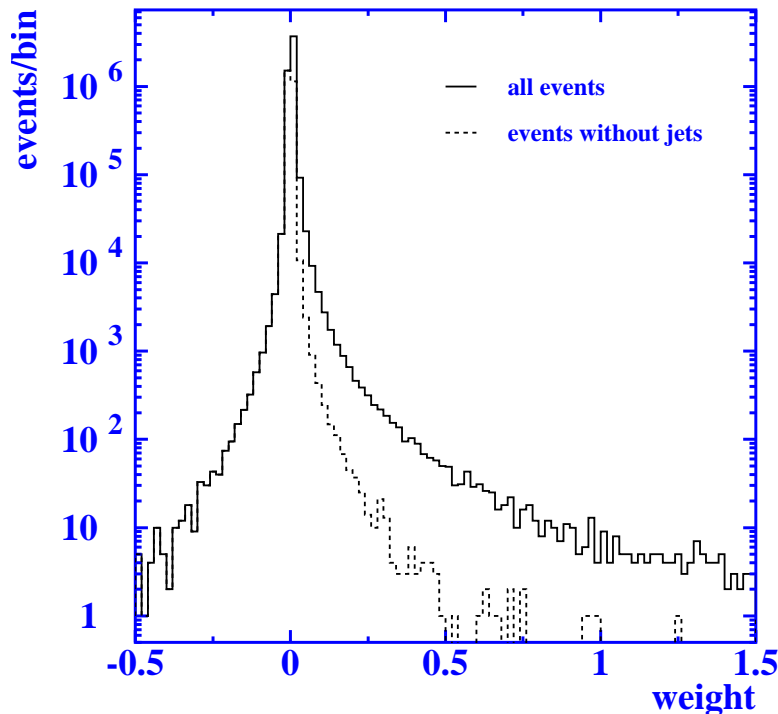

Figure 2: *Distribution of weights for* W^+W^- *events generated for the LHC by the BHO program*

The program MC@NLO [11] generates W^+W^-, $W^{\pm}Z$, ZZ and some other non di-boson processes. The generation is done in two steps. The first step, called NLO, generates only the hard interaction, producing the di-bosons and, for part of the events, the outgoing ME parton, just like the BHO generator. The generated events are written to a file. The second step, called MC, reads the generated events from the file and process them with HERWIG to simulate the underlying events, the parton shower and hadronization processes. Special care is taken in the parton shower process of HERWIG to avoid double counting of ME and SH partons. Typically, 85% of the events are generated with weight of 1 and the rest with weight of -1. Multiple interactions between the incoming partons, included in PYTHIA, are not part of HERWIG, but can be still included by running HERWIG in the MC step together with the JIMMY program [12]. As in BHO, the gauge bosons are produced with their nominal mass without width. Unfortunately, anomalous couplings are not implemented. Apart from W-pair production where both W's decay into leptons, the decay of the gauge bosons is done in the second step, which does not have the information on the boson helicity states. Therefore, the gauge bosons decay isotropically. This is a problem mainly for analysis aiming at polarization measurements.

Table 1 summarizes the characteristics of the three different Monte Carlo programs described above.

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Generator	PYTHIA	BHO	MC@NLO+JIMMY
Processes	all	W^+W^-, $W^\pm Z$, $W^\pm\gamma$, $Z\gamma$	W^+W^-, $W^\pm Z$, ZZ
NLO	×	√	√
Boson width	√	×	×
Spin information	√	√	×
Anomalous TGC	×	√	×
Fragmentation, hadronization, underlying event	√	×	√

Table 1: Properties of the different Monte Carlo programs

	Generator	PYTHIA	BHO		MC@NLO+JIMMY
		LO	LO	NLO	NLO
W^+W^-	Total cross section [pb]	3.510	3.774	4.978	5.211
	Fraction of events with jets	0.268	0.478		0.311
	Fraction of g,q,$\overline{q}$ jets	1., 0., 0.	0.37, 0.47, 0.16		0.58, 0.31, 0.11
		LO	LO	NLO	NLO
W^+Z	Total cross section [pb]	0.257	0.273	0.417	0.432
	Fraction of events with jets	0.294	0.347		0.474
	Fraction of g,q,$\overline{q}$ jets	1., 0., 0.	0.30, 0.55, 0.15		0.58, 0.33, 0.09
		LO	LO	NLO	NLO
W^-Z	Total cross section [pb]	0.160	0.171	0.262	0.270
	Fraction of events with jets	0.286	0.348		0.472
	Fraction of g,q,$\overline{q}$ jets	1., 0., 0.	0.27, 0.53, 0.20		0.56, 0.32, 0.12
		LO	LO	NLO	
$W^+\gamma$	Total cross section [pb]	3.349	3.996	8.707	-
	Fraction of events with jets	0.183	0.438		-
	Fraction of g,q,$\overline{q}$ jets	1., 0., 0.	0.18, 0.57, 0.25		-
		LO	LO	NLO	
$W^-\gamma$	Total cross section [pb]	2.226	2.681	6.418	-
	Fraction of events with jets	0.180	0.448		-
	Fraction of g,q,$\overline{q}$ jets	1., 0., 0.	0.15, 0.65, 0.20		-
		LO			NLO
ZZ	Total cross section [pb]	0.0424	-	-	0.0682
	Fraction of events with jets	0.278	-		0.365
	Fraction of g,q,$\overline{q}$ jets	1., 0., 0.	-		0.85, 0.11, 0.04
		LO	LO	NLO	
$Z\gamma$	Total cross section [pb]	1.471	1.756	2.433	-
	Fraction of events with jets	0.190	0.364		-
	Fraction of g,q,$\overline{q}$ jets	1., 0., 0.	0.32, 0.52, 0.16		-

Table 2: Total cross section, multiplied by the branching fraction for decays into electrons and muons, fraction of events with jets with $p_T > 30$ GeV, and, out of these events, the fractions of events where the jet is due to gluon, quark and anti-quark

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For a detailed comparison between the three Monte Carlo programs, large samples of events have been generated by each program for all implemented di-boson final states. The CTEQ6M [13] Parton Distribution Functions (PDF's) have been used for all Monte Carlo programs, utilizing the LHAPDF [14] interface. The $W^{\pm}\gamma$ and $Z\gamma$ final states have been generated with a 30 GeV lower photon p_T cutoff[4]. The Z bosons in ZZ and $Z\gamma$ as produced in PYTHIA can be virtual and mix with a virtual photon, including interference. Therefore, a cut on these events has been applied, requiring the invariant mass of the generated Z decay products to be within ± 10 GeV from the Z nominal mass. All the quoted values and distributions below refer to the events after these cuts.

The total cross-section values, multiplied by the branching fractions for decays into electrons and muons, are listed in Table 2. The PYTHIA LO values are lower by 7% (20%) than the LO values of BHO for final states without (with) photon. The reason for the difference is not clear to us. The electroweak parameters in PYTHIA do not coincide exactly with those of BHO, but this can explain a difference of no more than 3%. The differences between the BHO and MC@NLO cross-section values are smaller, and the BHO values are lower by 3 - 5%. A detailed study to understand the source of these differences is out of the scope of this paper. The K-factors, which are the ratios between the NLO and LO cross-section values vary from 1.3 for W^+W^- to 2.2 - 2.4 for $W^{\pm}\gamma$. These factors are much larger than the differences between the various programs, and they demonstrate the importance of the NLO corrections.

An interesting kinematic variable to be compared between the different Monte Carlo programs is the transverse momentum of the di-boson system, originating from one or more jets which are produced along the two bosons. This variable is referred below as jet p_T, and events with jets are defined as events with jet p_T above 30 GeV. Table 2 shows the fraction of events with jets for the various Monte Carlo generators. Large differences are observed between the different generators. In particular, in PYTHIA, having only SH jets, the fraction of events with jets, as expected, is always smaller, compared with the other programs. There are even larger differences between BHO and MC@NLO.

For a clearer view, the jet p_T distributions are plotted in Fig. 3 for W^+W^-, W^+Z, $W^+\gamma$ and ZZ events. The distributions for W^-Z ($W^-\gamma$ and $Z\gamma$) are similar to those for W^+Z ($W^+\gamma$). The distributions for BHO and MC@NLO look similar but they are not exactly the same and, as already mentioned, the fractions of events with jet p_T above 30 GeV is significantly different. The PYTHIA distributions are softer for most cases, differing from the other generators, by an amount depending strongly on the final state. It is maximal for final states with photons and almost vanishing for ZZ. This observation needs further investigation which is beyond the scope of this paper. For MC@NLO the 4-momentum of the outgoing ME parton is available in the generated event record. The rest of the event p_T is assigned to the SH partons. The separate contributions of the ME and SH partons to the jet p_T are shown in Fig. 3. As expected, the SH p_T distribution is much softer than the ME one.

Large differences between the Monte Carlo generators exist also in the relative contributions of the three processes leading to events of di-bosons with jets, as listed in Table 2. The SH partons in PYTHIA start from gluons emitted from the quark lines (Fig. 1c,d), whereas in BHO there are contributions also from the processes qg→VVq and $\overline{q}$g→VV$\overline{q}$, corresponding to Fig. 1(e-h). The ratios between these contributions are according to the NLO di-boson ME

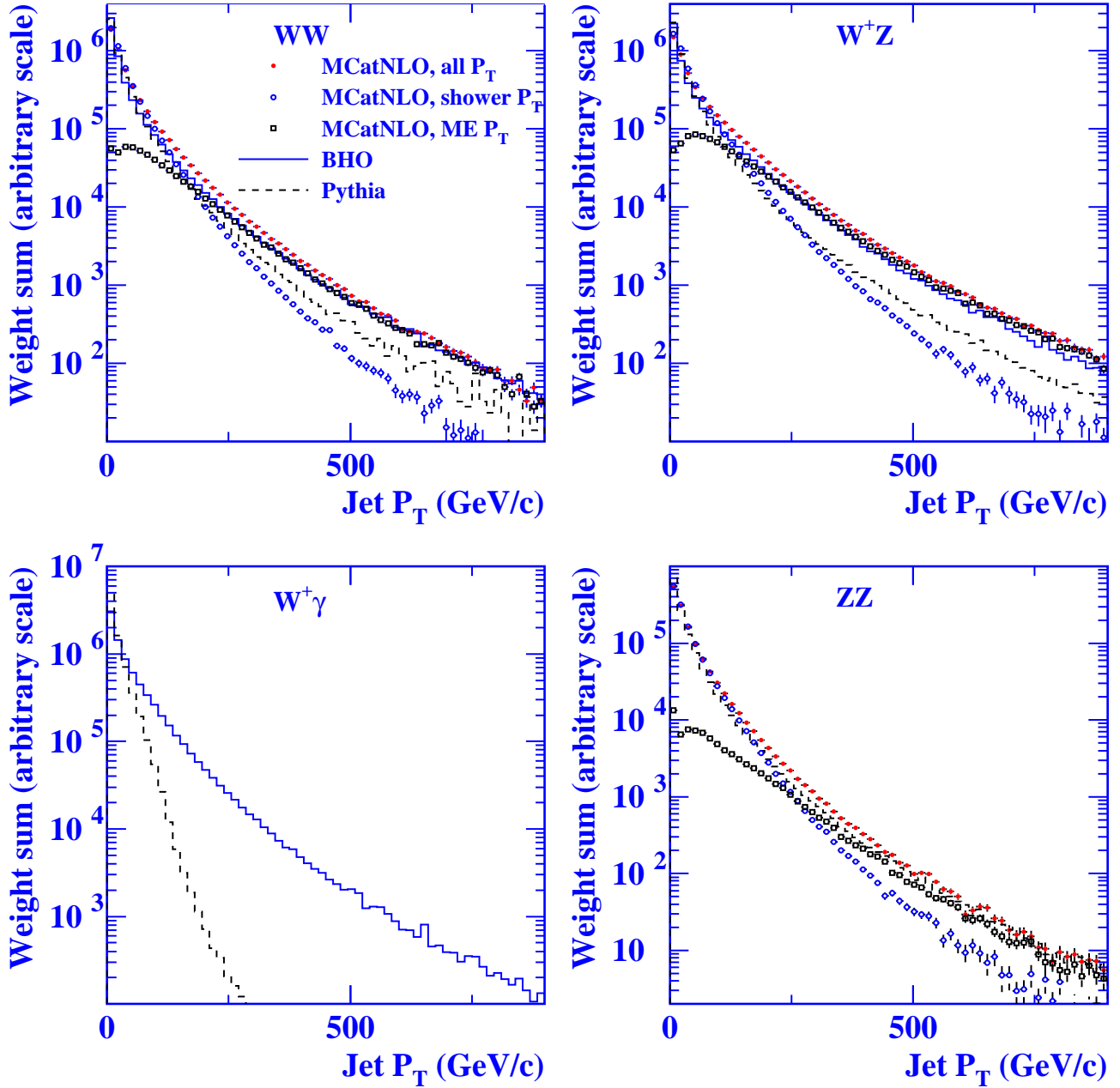[4]All transverse momenta in this paper are with respect to the proton beam direction.

Figure 3: p_T distribution of the di-boson system for W^+W^-, W^+Z, $W^+\gamma$ and ZZ. In each plot, the distributions from the various available Monte Carlo programs are normalized to each other.

(actually, the LO ME of di-boson + jet). In MC@NLO the situation is more complex. In the NLO process, in anticipation of the following MC step, the majority of the generated events do not have outgoing partons. This is demonstrated in the ME p_T distributions of Fig. 3, which contain only those events with outgoing partons and falls below the total p_T distributions. Adding SH partons to those events, does not change their classification as events with outgoing gluon, quark or anti-quark. On the other hand, all those events generated in the NLO process without outgoing partons, and obtain SH partons with p_T above 30 GeV, are classified as events with outgoing gluons. This is why the fraction of events with outgoing gluons is much higher at MC@NLO compared to BHO. However, as expected, the ratio between events with outgoing quarks and with outgoing anti-quarks is approximately the same for these two Monte Carlo programs.

Since the distributions of other kinematic variables are expected to be correlated with the jet p_T distribution and with the classification of the jet production process, one should not be surprised to see, for events with jets, some disagreements between those distributions. This will be shown in the next section.

3   Monte Carlo Event Weighting

So far, many Monte Carlo samples of di-boson events have been generated by the Tevatron and LHC collaborations using the PYTHIA and MC@NLO programs. These samples passed high CPU-consuming detector simulation processes. As noted in the previous section, the PYTHIA events do not include NLO effects. The total cross section and some differential distributions can be corrected by K-factors, but this is not completely satisfactory, since it is not clear whether those correction factors are not modified by the selection cuts. This is why more and more samples are produced with MC@NLO, but as explained in the previous section, this program also ignores some important physics aspects such as spin information for most of the di-boson final states and the anomalous TGC's. Fortunately, these missing effects exist in the BHO program, but this program cannot be used for event generation, since it lacks the underlying event and the parton showering and hadronization processes.

In order to use the advantages of the BHO program, its ME calculation code has been extracted, so that it allows calculating for each given generated event a weight value which is proportional to the cross section. This can be done under different conditions. For example, it can include the full decay of the bosons into leptons using the boson helicity information. Another possibility is to ignore the boson decay, summing over the boson helicities. This would imitate the treatment in MC@NLO. Taking e.g. an event generated by MC@NLO, the ratio between the weight values calculated with and without boson decay, can be used to weight that event. The MC@NLO sample, after this weighting, should have the correct angular distributions as expected for events with the spin information. In the same manner, weighting by the ratio between the weight values with and without an anomalous coupling would introducing the effect of this coupling to events generated without anomalous couplings, e.g. by PYTHIA or MC@NLO. Any systematic uncertainty related to the ME calculation, such as electro-weak parameters, PDF's or α_s can be investigated using a similar weighting.

The ME calculation program handles separately each of the processes described in Fig. 1(a-j),

and for each flavor of the incoming quarks. For events without outgoing partons, only the Born term is used, in order to avoid negative weights. In any case, for all the events produced by PYTHIA or MC@NLO the di-boson system has some transverse momentum value and are then interpreted as events with one outgoing parton. The momentum of this outgoing parton is the SH parton momentum, to which one adds the ME parton momentum, if it exists, namely, if the event was generated by the NLO step of MC@NLO with an outgoing parton. There is some ambiguity in the calculation of the SH parton momentum. The transverse part is known, since it is merely the vector needed to balance the transverse momentum vector of the di-boson and ME parton (if present) system. The longitudinal part is assumed arbitrarily to vanish in that system. The identity of the parton is determined as before, namely it is the identity of the ME parton, if present; otherwise, it is assumed to be a gluon. The resulting event has all the information needed for the calculation of its weight under different conditions to obtain the required weight ratios.

This event weighting method has been tested, as a method to introduce the correct spin information, and to introduce anomalous couplings. This has been done for all di-boson final states. Few examples are shown below.

3.1 Spin Information Weighting

To test the spin information weighting, it is necessary to look at the distributions of the production and decay angles. These angles are defined in Fig. 4, for W$^+$Z events.
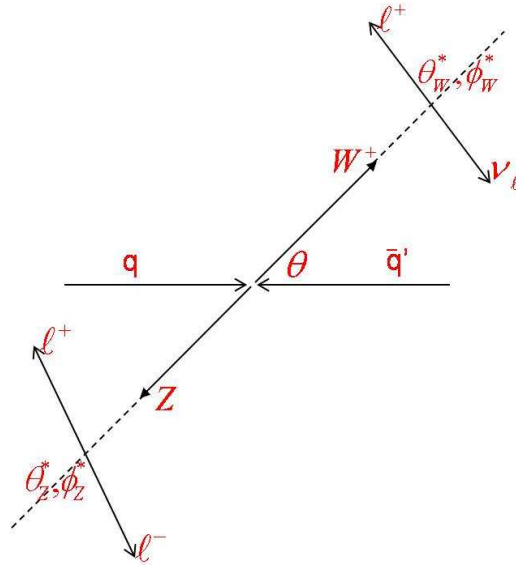

Figure 4: *Production and decay angles of the* W$^+$Z *system*

The production angle, θ, is the angle between the incoming quark direction and the outgoing W$^+$, at the rest-frame of the W$^+$Z system. Obviously, Fig. 4 does not describe events with jets, in particular the case where one of the incoming parton is a gluon. Even in events without jets the direction of the quark cannot be distinguished experimentally from the direction of the anti-quark. To avoid these difficulties, the direction of the di-boson system boost in the

laboratory frame, $\mathbf{z_{BB}}$, is used instead. This is valid also for events with jets, where it does not necessarily coincide with the direction of any of the incoming beams. This definition relies on the fact that the incoming quark in a proton beam, which can be a valence quark, is expected, on the average, to be more energetic than the anti-quark coming always from the sea of the opposite proton. Therefore, for most of the events, the overall boost of the di-boson system is expected to be close to the incoming quark direction.

The orbital and azimuthal angles, θ^*, ϕ^*, of the charged lepton (anti-lepton) decaying from the Z (W^+) are defined in the rest-frame of the decaying boson. The z-axis in this system is defined as the boson direction in the rest-frame of the di-boson system, $\mathbf{z_B}$. The y-axis is defined to be orthogonal to the di-boson production plane, namely, in the direction of $\mathbf{z_{BB}} \times \mathbf{z_B}$, and the x-axis is in the di-boson production plane, forming together with the two other axes a right-handed Cartesian coordinate system.

Distributions of the production and some of the decay angles in W^+Z events are shown in Figs. 5,6, separately for events without and with jets. All the distributions are normalized to the same arbitrary total sum of weights. The distributions for MC@NLO before and after the weighting to correct for the missing spin information are shown by the solid and open points respectively. For the production angle, the open points are not visible, since the distributions with and without weighting are identical, as expected. Contrarily, for the decay angles, all the distributions before weighting are uniform, and after weighting are similar to those from PYTHIA and BHO. Some differences do exist, in particular for events with jets, but they are at the same size as the differences between PYTHIA and BHO. Differences are present also in the production angle distributions, thus they cannot be entirely attributed to the weighting. For events without jets, there is a very nice agreement between the weighted MC@NLO and PYTHIA, whereas in BHO there is a slight excess of events with W^+'s produced along the beam axis, and a small deficiency of W^+'s decaying into a backward charged lepton. Larger differences are present in the distributions of events with jets, in particular between PYTHIA and the other two generators. This is not surprising as it was already shown that PYTHIA does not describe properly events with high p_T jets. It would be interesting to see whether also the differences between the weighted MC@NLO and BHO can be related to the differences in the jet p_T distributions and in the fraction of gluon jets discussed in the previous section. To check that, the BHO events have been weighted to give the same number of gluon, quark and anti-quark jet events in each p_T bin. The resulting BHO distributions after this p_T weighting (dotted lines in Figs. 5,6) agree almost perfectly with MC@NLO. Even for the low p_T plots, corresponding to the lowest two bins in the p_T distribution[5], the agreement improves, in particular for the production angle, where the dotted line is not visible as it coincides with the dashed PYTHIA line.

The same comparison of angular distributions has been done for all other di-boson final states with similar results. For events with W^+W^- decaying into leptons, the MC@NLO generator already contains the spin information. Nevertheless, this channel is still included in the code for completeness as well as for the TGC and other applications. To check the spin information part, the inverse of the spin information weighting has been applied on the events to see if the decay angular dependence is removed, and indeed, the decay angle distributions become uniform and the production angle distribution is preserved. As a further check, the spin information in the W-decays have been removed by regeneration of the W decay product four-momenta

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[5]The first p_T bin in BHO includes also events without any jet. The fraction of these events had to be modified as well, in order to reach the good agreement with the other generators.
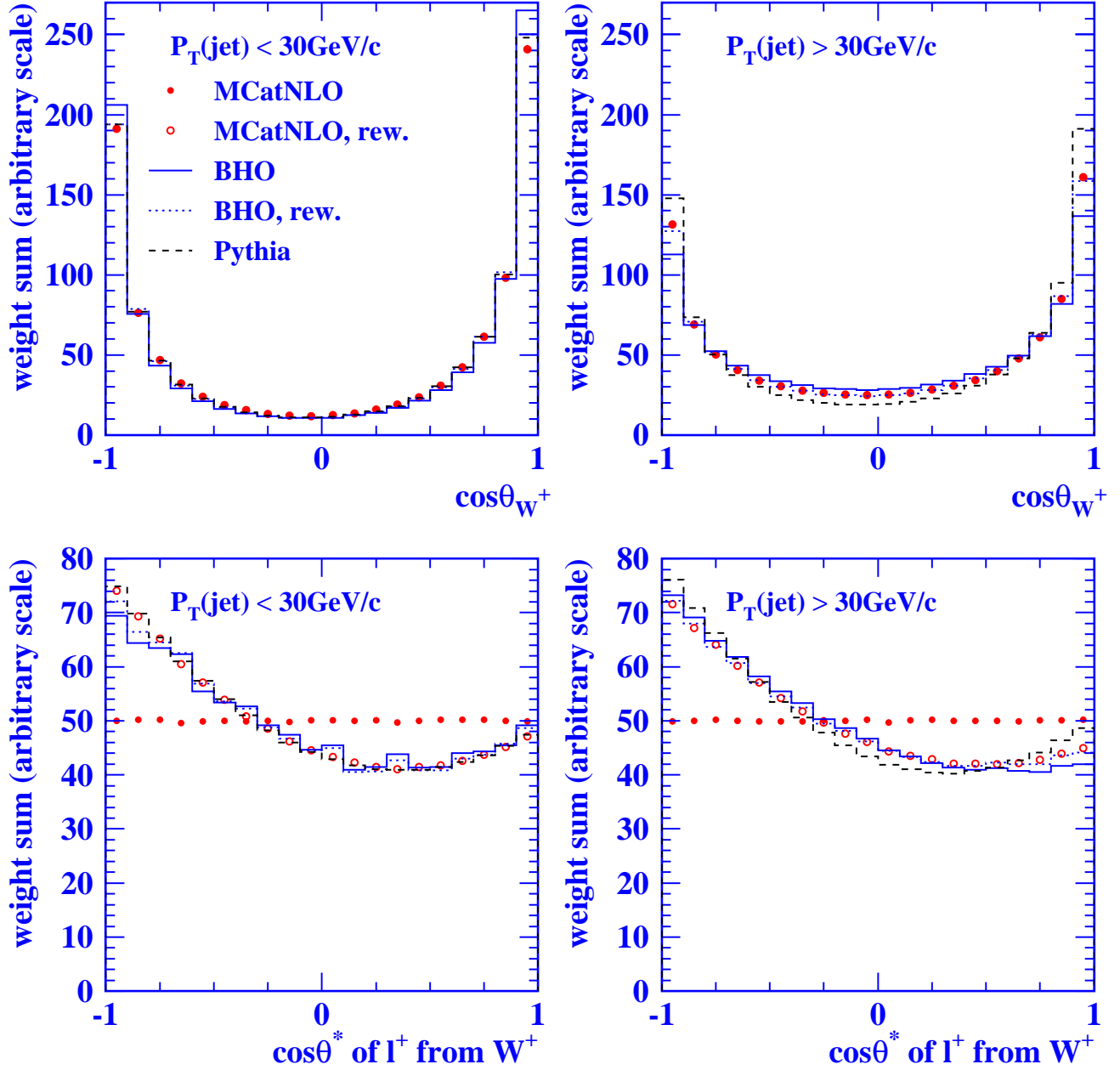
Angular Distributions in ZW$^+$ Events

Figure 5: *Distributions of the W-production and decay angles in W$^+$Z events. See text for a detailed definition of the angles and explanation of the different distributions.*

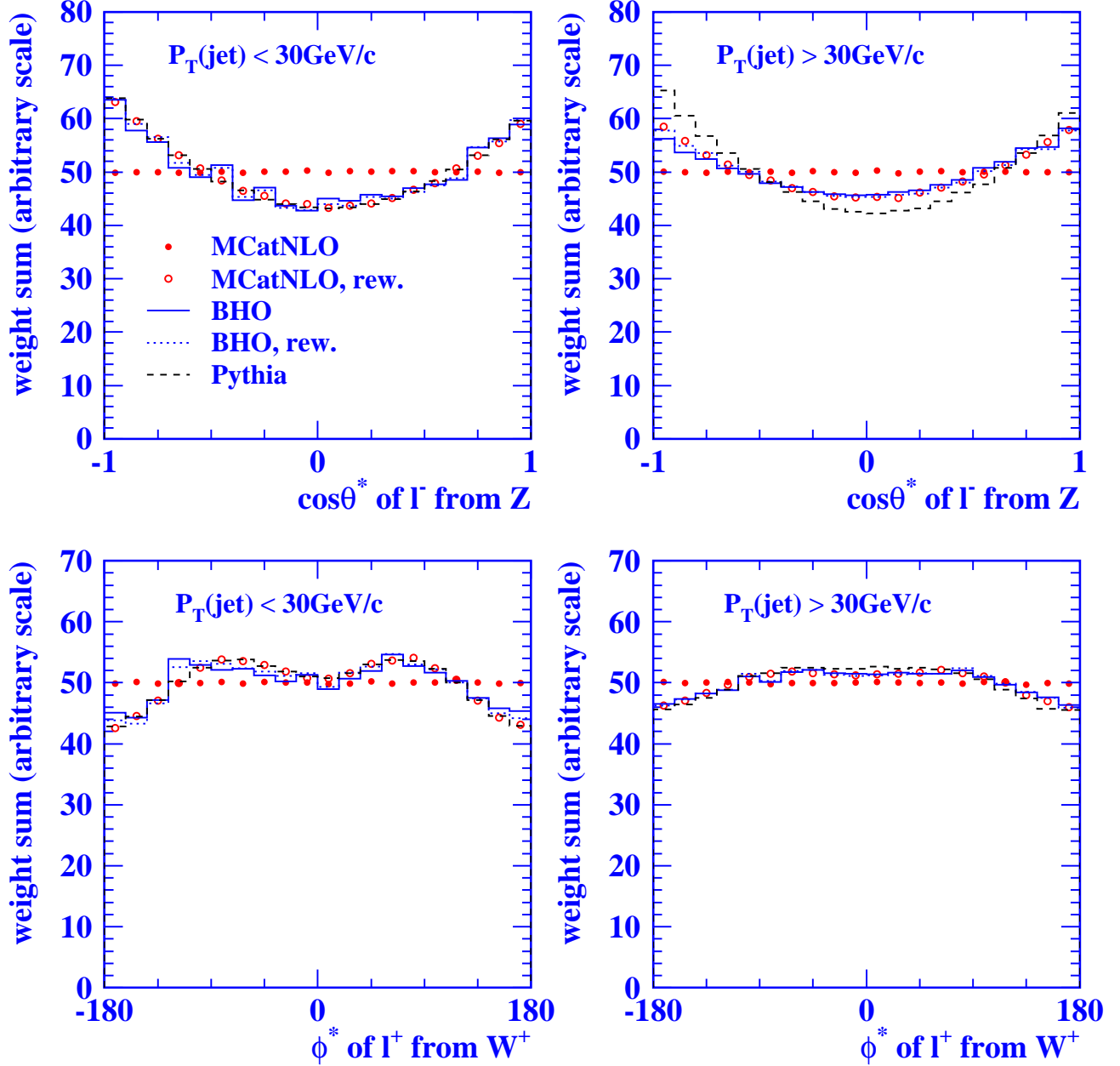# Angular Distributions in ZW$^+$ Events

Figure 6: *Distributions of the orbital Z-decay angle and the azimuthal W-decay angle in W$^+$Z events. See text for a detailed definition of the angles and explanation of the different distributions.*

corresponding to a uniform decay. These modified events have been weighted to re-introduce the spin information and the resulting decay angle distributions have been compared with the original ones. Again, a very good agreement has been achieved. As for the W^+Z case, the agreement with BHO is rather good and improves after the jet p_T weighting of the BHO events.

The ZZ final state is not generated by the BHO program, but some part of the BHO code covers this channel, without anomalous couplings. Consequently, this channel is included in the weighting code and has been used to introduce spin information to MC@NLO events. The agreement of the resulting distributions with PYTHIA is excellent for events without jets, and a bit worse for events with jets, as for the other final states.

The $W^\pm\gamma$ and $Z\gamma$ channels are not included in MC@NLO, so the only comparison to be done is between BHO and PYTHIA. The agreement between the angular distributions of these two generators is not so good, unless the BHO generator is modified to mimic PYTHIA as much as possible, namely, using the Born matrix element to generate events without jets, and in events with jets, only those events with gluon jets are included with jet p_T weighting.

3.2   TGC Weighting

Anomalous TGC's mainly affect events at high c.m. energies of the hardly interacting partons and large production angles where the contribution of the triple gauge vertex s-channel diagrams, e.g. in Fig. 1b, is enhanced with respect to the t-channel diagrams (see, e.g. Fig. 1a). The most convenient kinematic variable to use, is the transverse momentum of one of the outgoing bosons which increases with both c.m. energy and production angle, and is invariant under the boost of the hardly interacting system. For W^+W^- events, where both W's decay into a charged lepton and a neutrino and the W-transverse momentum cannot be reconstructed, the transverse momentum of the charged lepton is used.

As an example, Fig. 7 shows the $p_T(Z)$ distributions for W^+Z events for the case of the Standard Model and for the case of anomalous coupling $\lambda_z = 0.1$. Also here, we distinguish between events without and with jets. The difference between the distributions for the Standard Model and for anomalous coupling is remarkable, already for $p_T(Z)$ above 150 GeV, and steeply increases with p_T. The anomalous coupling value used here has been chosen to correspond to a large effect on the distribution, in order to have a good sensitivity to any possible disagreement between the different Monte Carlo generators and our calculated weight ratios, which have been applied on the MC@NLO and the PYTHIA events.

The MC@NLO events have been weighted to include also the spin information. Their distributions, shown by the solid points, have, for events without jets, a nice agreement with the BHO and PYTHIA distributions (solid and dashed lines, respectively). This agreement holds for the Standard Model, as well as for anomalous coupling. For events with jets, the agreement is worse, in particular for PYTHIA, which, as discussed above, does not describe well this kind of events. For events with jets, the discrepancy between BHO and MC@NLO is less remarkable, and reduces further when the BHO events are weighted according to their jet p_T (dotted line), as described above.

Similar behavior is seen also for other anomalous couplings, such as $\Delta\kappa_z$ and Δg_1^z. The sen-

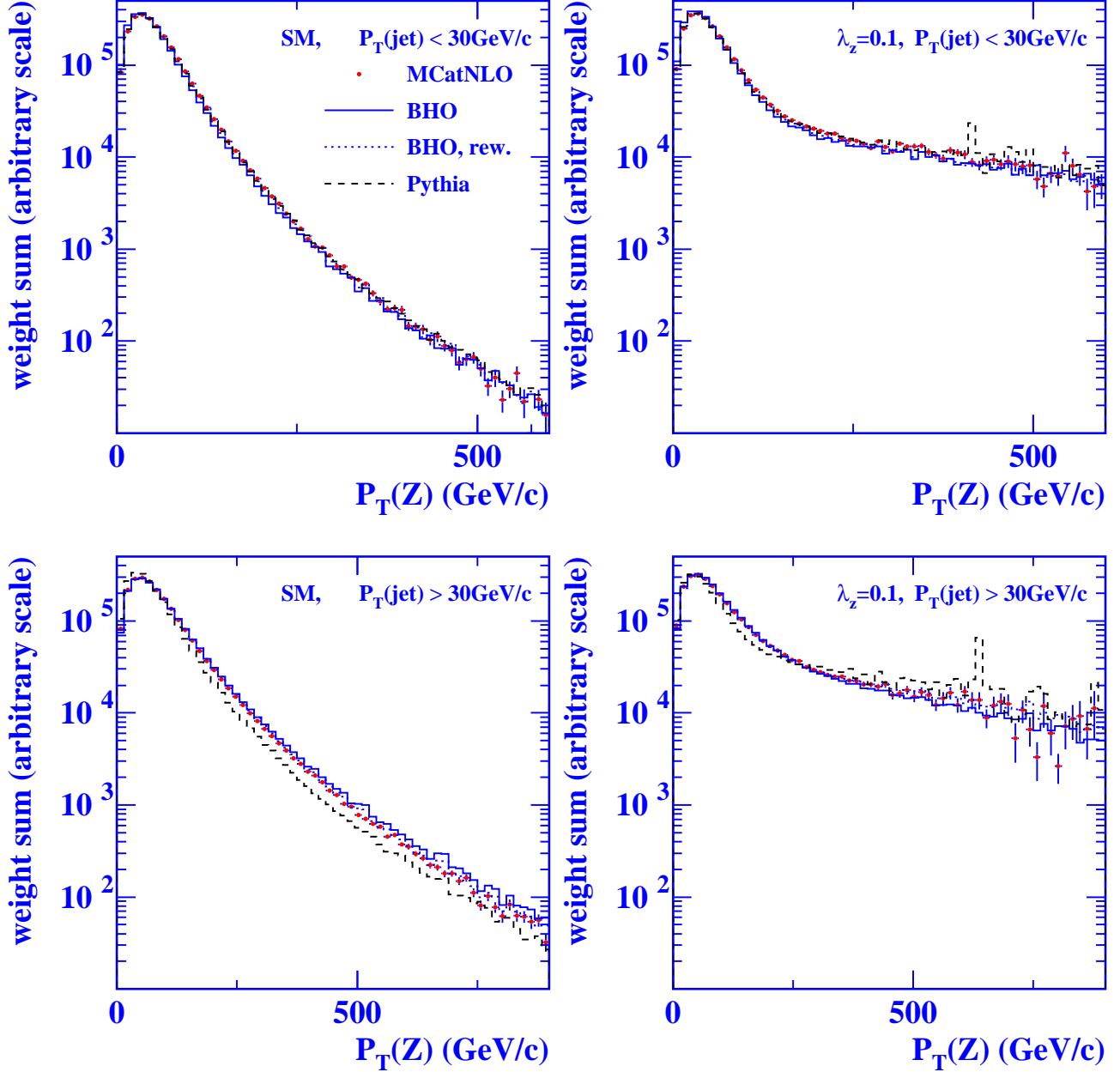# $P_T(Z)$ Distributions in ZW^+ Events

Figure 7: *Transverse momentum distributions of the Z in* W^+Z *events for the case of the Standard Model and for the case of anomalous coupling* $\lambda_z = 0.1$ *separately for events without and with jets*

sitivity for these couplings is, however, much smaller, and larger values of the couplings are needed to produce similar effects on the $p_T(Z)$ distribution.

The same study has been repeated also for the other di-boson channels. The W^-Z channel has been investigated in exactly the same way. For the $W^\pm\gamma$ channels, the Standard Model has been compared with the anomalous couplings λ_γ and $\Delta\kappa_\gamma$. For W^+W^- events, the investigated TGC's were λ_γ, $\Delta\kappa_\gamma$ and Δg_1^z, assuming the following SU(2)×U(1) relations between the $WW\gamma$ and WWZ couplings [15, 16],

$$\begin{aligned}\Delta\kappa_z &= -\Delta\kappa_\gamma\tan^2\theta_w + \Delta g_1^z, \\ \lambda_z &= \lambda_\gamma.\end{aligned}$$

These relations are motivated by precision measurements on the Z resonance and lower energy data, and have been used by the LEP collaborations [1]. For the $Z\gamma$ channel, the neutral current anomalous couplings, h_i^γ and h_i^Z (i=1,2,3,4) have been tested. To avoid unitarity violation, all the anomalous couplings in the weighting program, following the BHO generator, have been assumed to fall off with increasing invariant mass of the di-boson system, M_{VV} according to the following dipole form factor relation [17],

$$\alpha(M_{VV}) = \frac{\alpha(0)}{(1 + (M_{VV}/\Lambda_{FF})^2)^n}, \tag{1}$$

where α stands for any anomalous TGC, and the form factor scale, Λ_{FF} has been taken as 10 TeV. The power n is 2 for the $WW\gamma$ and WWZ couplings, whereas for h_i^γ and h_i^Z it is 3 (4) for i odd (even).

4   Summary and Discussion

This study of di-boson Monte Carlo event generators shows a nice agreement between the differential distributions of various kinematic variables for events without jets, although the total cross-section values differ by few percents. Events with jets, on the other hand, are generated differently in each generator. Consequently, the jet p_T distributions differ, and even the identities of the partons forming the jets are not distributed in the same way. These differences affect the distributions of kinematic variables, including those which are not directly related with jets. None of the Monte Carlo generators is expected to give a precise description of jet production, which might be a source of systematic uncertainty in any analysis which is using Monte Carlo events. This uncertainty can be minimized in analyses where events with jets are suppressed by the event selection cuts. It will also be interesting to have separate studies of events with jets in the real data, in order to be able to choose the most appropriate Monte Carlo generator and tune its free parameters.

The weighting program described in this paper, when applied to MC@NLO and PYTHIA events without jets, seems to give a sample with the correct kinematic distributions as obtained from BHO. This weighting can be used to introduce TGC and spin effects wherever needed, as well as for investigation of Monte Carlo generator related systematics.

One disadvantage of weighting events is the loss in statistical significance, in particular for the case where the distribution of the weight ratios used for the weighting is broad. The weight ratio
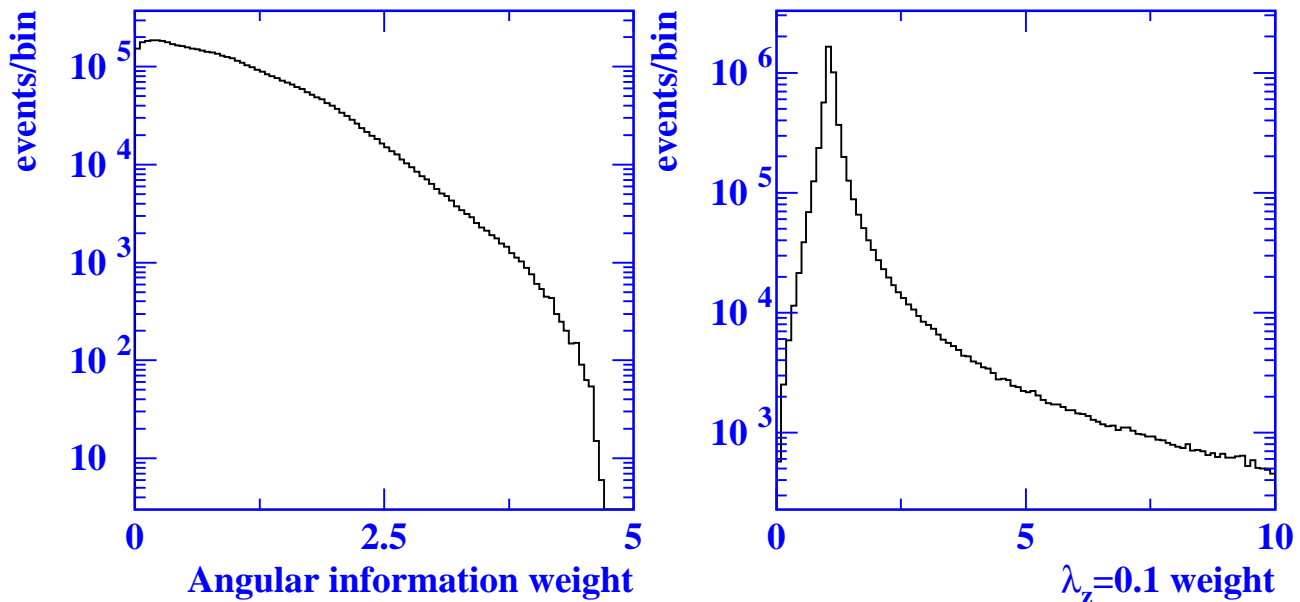
Figure 8: *Distributions of weight ratios used for W^+Z events to introduce spin information and anomalous TGC λ_z=0.1*

distributions for W^+Z events are plotted in Fig. 8. The distribution of spin information weight ratios is rather narrow without long tails. Applying these weight ratios increases the statistical errors of the angular distributions by a factor of ≈ 1.6. The distribution of TGC information weight ratios is centered around 1, but has a long tail at high weight ratio values. The events with weight ratio around 1, forming the majority of the sample, are those with low $p_T(Z)$ and low sensitivity to anomalous TGC's. The events in the tail correspond to high $p_T(Z)$, and contribute most of the sensitivity to the TGC analysis. Unfortunately, these very high weight ratios cause a significant increase in the Monte Carlo statistical errors at this interesting high p_T region.

The finite boson width which is missing in MC@NLO events cannot be introduced by event weighting. This problem, however, is not expected to have a significant effect, unless the di-bosons are produced close to their kinematic threshold. The nice agreement for events without jets between the distributions of PYTHIA and MC@NLO demonstrates that the boson width in PYTHIA does not play an important rôle.

Appendix: A Short Manual of the Weighting Package

The weighting package is available on `http://atlas2.tau.ac.il/bella/bhowei.html` in two FORTRAN files. The first one contains the main subroutine, `bhowei` and other subroutines called by the main one. All these routines have been rewritten following the original BHO code. The second file contains other subroutines which were taken from the original BHO code without modification. In addition to these two files, the user has to link the LHAPDF library which can be downloaded from `http://projects.hepforge.org/lhapdf/`. The calling sequence is,

```
call bhowei(mspin,xsec,ifail)
```

where,

`mspin`	(input, integer)	1 if spin information is needed, otherwise, 0
`xsec`	(output, real)	calculated weight, proportional to the cross section
`ifail`	(output, integer)	different from 0 in case of a problem

All the other information needed to run the program is inserted via common blocks.

The event data is inserted into the following common block,

```
common/cproc/id(7),p(0:3,7)
```

where `id` is an integer array of the PDG Monte Carlo particle codes [18] of the seven particles involved in the di-boson production. The first two are the incoming partons, the next four are the decay products of the two bosons and the last one is the outgoing parton. In case of a photon, its code, 22, is inserted in the position of the first decay product and the position of the second is filled with 0. Similarly, `id(7)`=0 in case of no outgoing parton. The real array `p` must contain the four-vectors of these particles at the same order as in `id`.

Variable	Type	Default	Description
`is`	integer	1	1 for pp, -1 for p$\bar{\text{p}}$
`npdf`	integer	10000	LHAGLUE number of PDF set
`loop`	integer	2	number of loops in α_s calculation
`cq`	real	1.	coefficient used to define q^2 (scale of α_s and PDF)
`iscale`	integer	2	q^2 definition flag, =1 for q^2 =`cq`·Mass(diboson+jet)^2, =2 for q^2=`cq`·Mass(diboson)^2, =3 for q^2=`cq`·p_T(jet)^2, =4 for q^2=`cq`·Mass(W)^2, =5 for q^2=`cq`·`mscale`^{2}
`mscale`	real	100.	used to define q^2 for `iscale`=5
`ecm`	real	14000.	c.m. energy of the interacting protons
`xlambda4`	real		Λ_{QCD} as calculated by LHAPDF
`lambda_scale`	real	10000.	TGC form factor scale, Λ_{FF}
`mw`	real	80.40	W mass
`mz`	real	91.187	Z mass
`mt`	real	175	t-quark mass
`gw`	real	2.12	W width
`gz`	real	2.487	Z width
`alfs`	real	0.116	$\alpha_s(m_Z^2)$
`alfem`	real	1/128.	$\alpha_{EM}(m_Z^2)$
`coscab2`	real	0.95	$\cos^2\theta_c$, θ_c is the Cabibbo angle

Table 3: Parameters in `common/const/`. All energy values are in GeV.

Constant parameters needed for the calculation are introduced in,

```
common/const/is,npdf,loop,iscale,ecm,cq,mscale,xlambda4,
           lambda_scale,mw,mz,mtop,gw,gz,alfs,alfem,coscab2
```

as explained in Table 3. Any calculation in the program using these constants is done for each call to `bhowei` and not just at the beginning of the run. Therefore, they can be modified before calling `bhowei`, and this can be done several times for each events with different parameter values in order to investigate their related systematics.

Anomalous couplings can be introduced via the following common blocks,

```
common/ctgc/dg1z,dkz,lamz,dkg,lamg
common/ntgc/hz(4),hg(4)
```

where `dg1z, dkz, lamz, dkg, lamg` are Δg_1^z, $\Delta \kappa_z$, λ_z, $\Delta \kappa_\gamma$, λ_γ, and `hz(4), hg(4)` are h_i^Z and h_i^γ (i=1,2,3,4) respectively.

Acknowledgments

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